Stellar influence on the photochemistry and spectra of terrestrial planets

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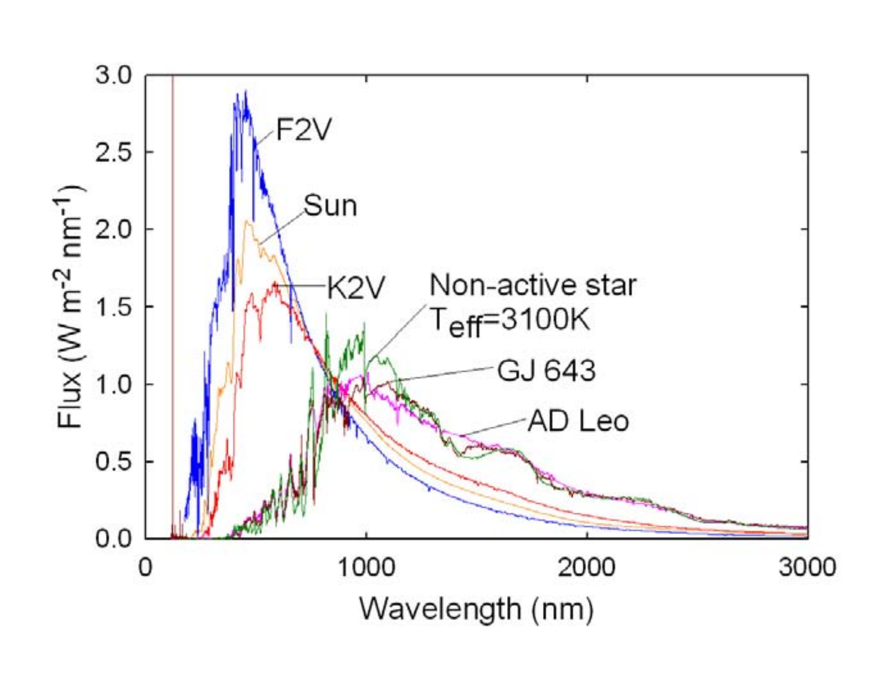
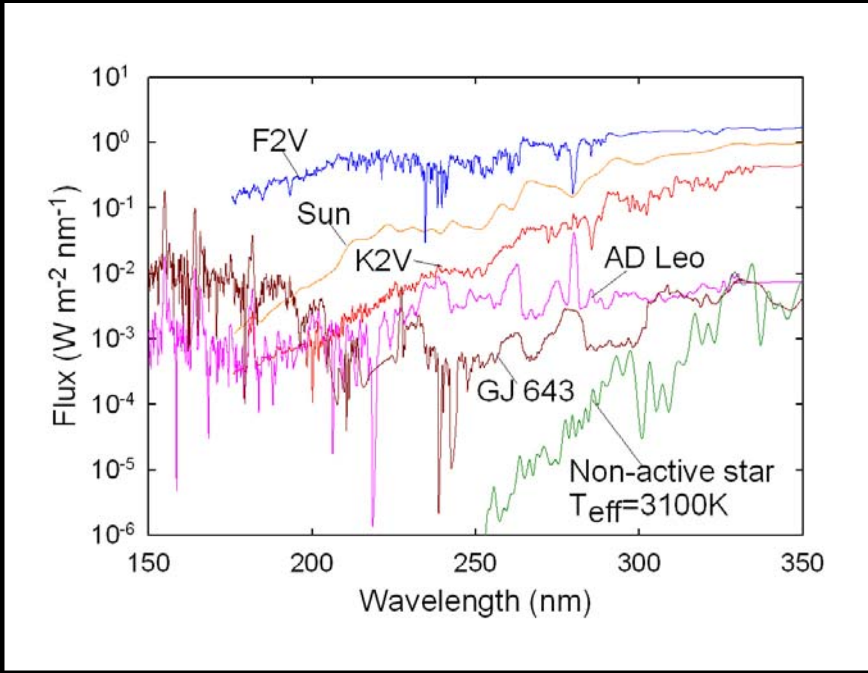
Overview

- The lifetime of a chemical compound in a habitable planet atmosphere depends on the parent star's UV flux.
- When considering how detectable a compound could be the UV environment should be considered.

Stellar spectra at the top of the planetary atmosphere





Spectra were normalized in order to get a surface temperature of 288 K on each planet.

Star	Spectral type	Effective temperature (K)	Age (yr)	Distance (pc)	Planet semi-major axis (AU)
Sun	G2V	5600	5×10^9	0	1
σ Bootis[a]	F2V	6700	2×10^9	12	1.69
ε Eridani[a]	K2V	5100	5×10^8	3.2	0.53
AD Leo[b]	M4.5V	3400	Young	4.9	0.16
Model[c]	M5V	3100			0.07

[a] Composite spectra were created using UV fluxes from the International Ultraviolet Explorer (IUE) and Kurucz synthetic spectra.
[b] Spectra from IUE, Pettersen and Hawley (1989), Leggett et al. (1996) and NextGen models.
[c] NextGen models from BaSeL website (www.astro.mat.uc.pt/BaSeL/).

Atmospheric models

- Climate model
  Radiative-convective 1-D model (Pavlov et al., 2000, *JGR* 105, 11981).

- Photochemical model
  1-D model for 55 chemical species linked by 219 reactions (Pavlov and Kasting, 2002, *Astrobiology* 2, 27).

- SMART radiative transfer model
  Generates high-resolution, angle dependent synthetic planetary spectra (Meadows and Crisp, 1996, *JGR* 101(E2), 4595).

Characteristics of the simulated planetary atmospheres:

- Present Earth concentrations for major species (N_2, O_2), and 355 ppm of CO_2
- Surface pressure of 1 atm.
- Fixed surface fluxes for biogenic compounds (H_2, CH_4, N_2O, CO, CH_3Cl), except for quiescent M stars.

Segura et al (2003, 2005)

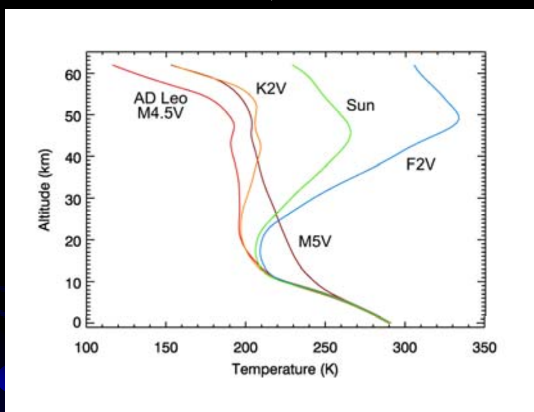
Spectra from F, G, K and M stars

Radiative-convective 1-D model (Pavlov et al., 2000, *JGR* 105, 11981).

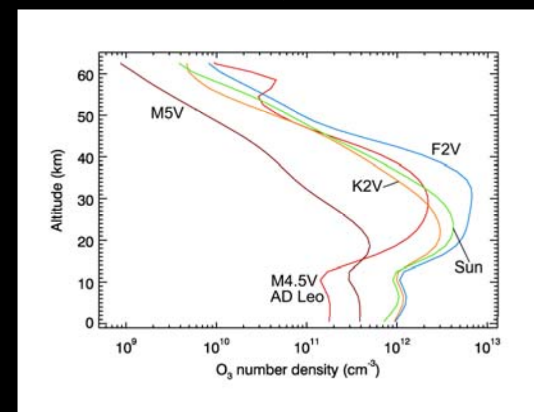
Temperature, tropospheric H_2O →

← Ozone, stratospheric H_2O

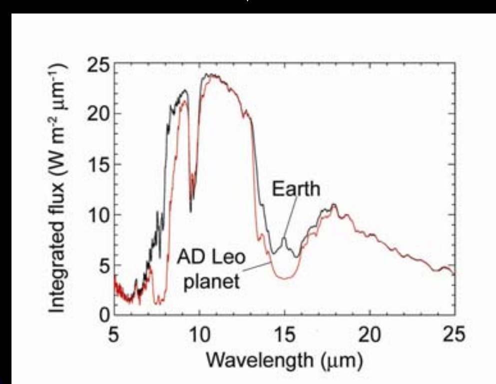
1-D photochemical model for 55 species linked by 219 reactions (Pavlov and Kasting, 2002, *Astrobiology* 2, 27).



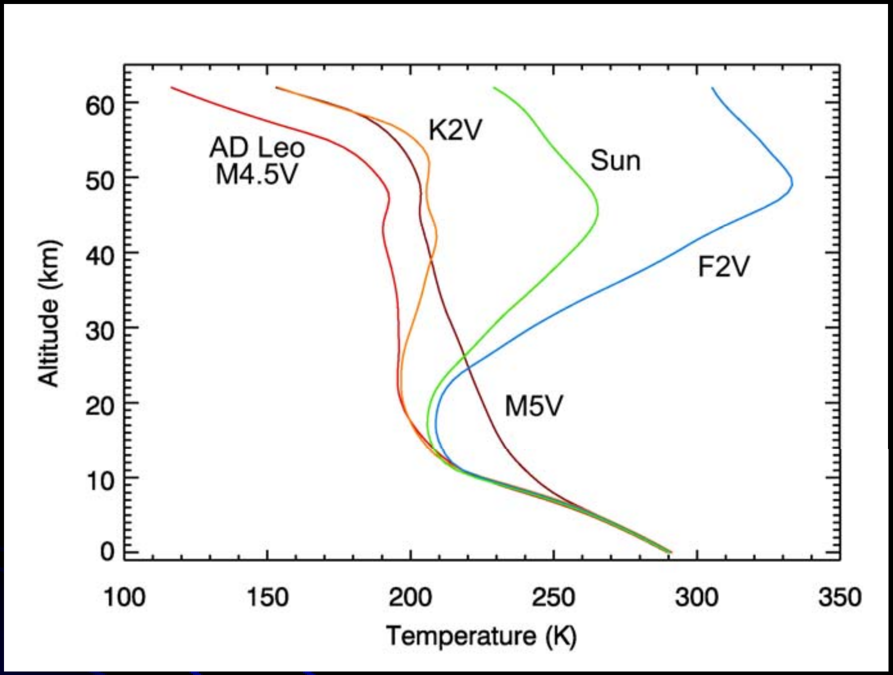
Profiles of Earth-like planets

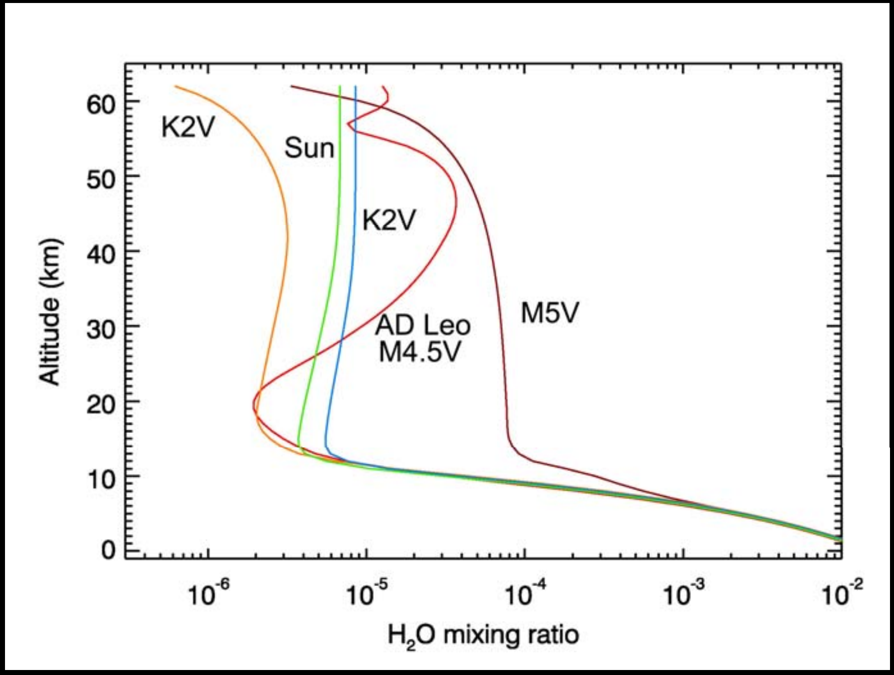


SMART radiative transfer model (Meadows and Crisp, 1996, *JGR* 101(E2), 4595).



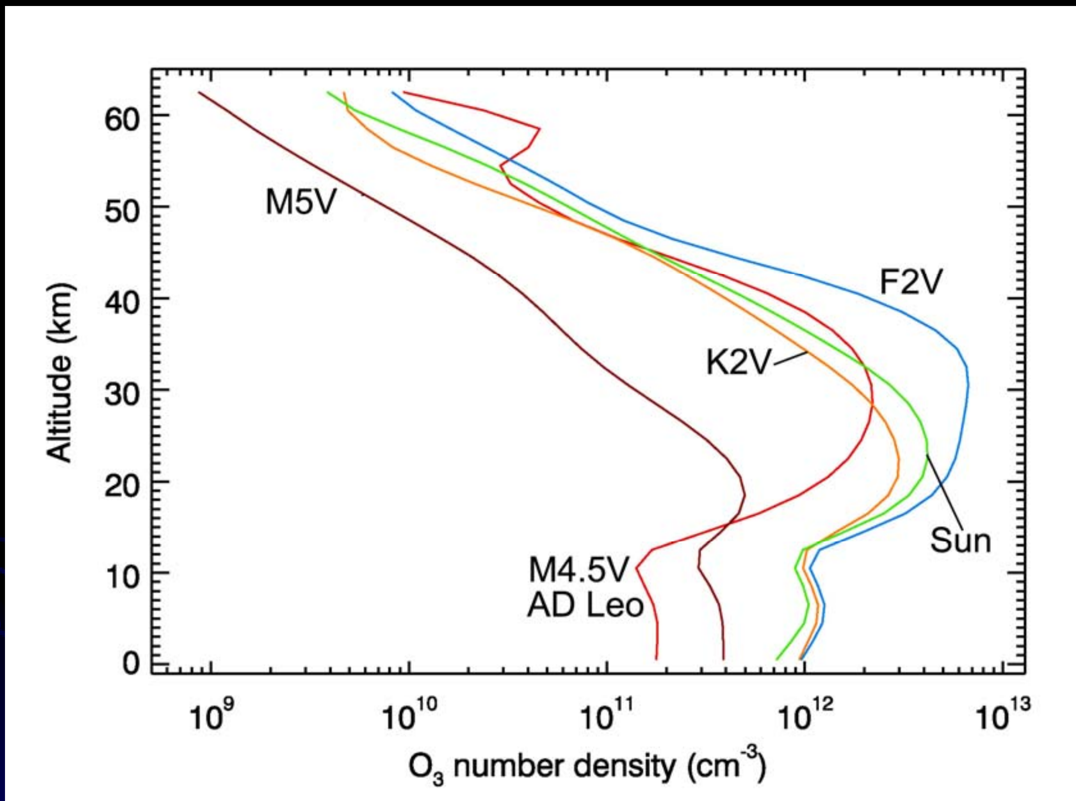
Temperature and H_2O profiles





From Segura et al. (2003, 2005)

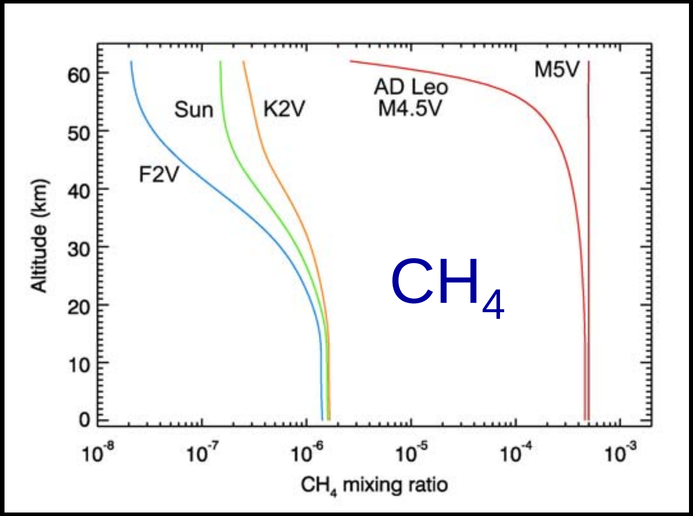
O_3 profiles



Parent star	O_3 column depth (cm^{-2})
Sun	8.4×10^{18}
F2V	1.6×10^{19}
K2V	6.6×10^{18}
AD Leo	4.4×10^{18}
M 3100	1.2×10^{18}

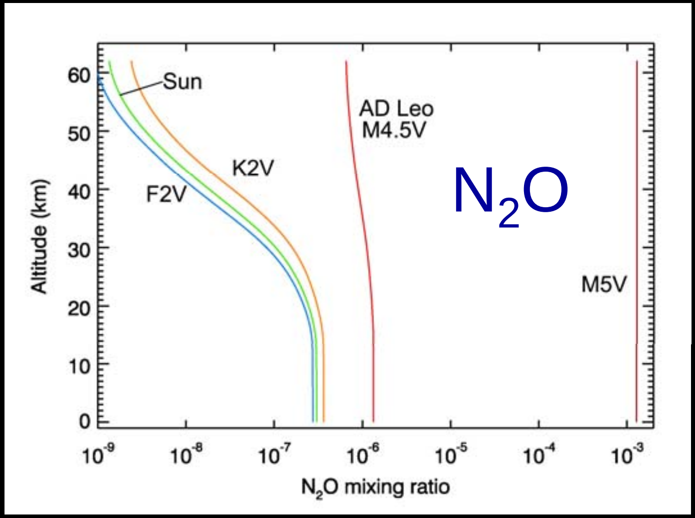
More UV more $O_3 \Rightarrow$ effective protection of the surface

Biosignatures



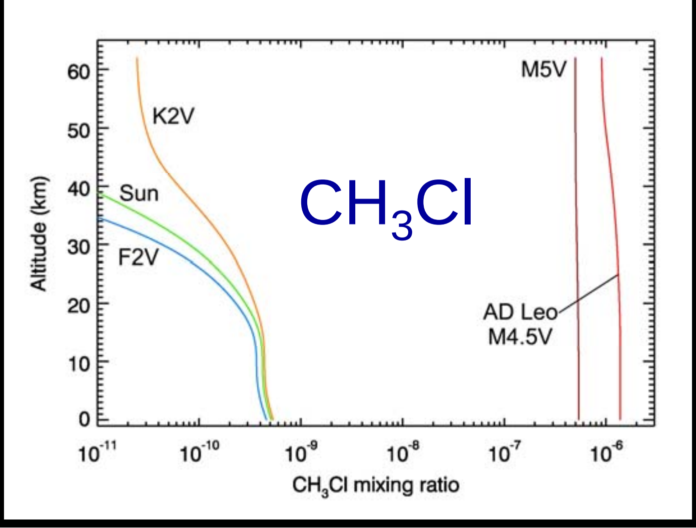
Methane flux = 9.5 x 10^{14} g/yr, except for non active M (2 x 10^{14} g/yr)

Sources: Wetlands, termites, oceans, waste decomposition, fossil fuels, biomass burning, domestic ruminants, rice paddies.



Nitrous oxide flux = 7.3 x 10^{12} g/yr

Sources: Biomass burning, tropical plants, planktonic algae (ocean), wood-rot fungi, wetlands, rice paddies.



Methyl chloride flux = 1.3 x 10^{13} g/yr

Sources: Oceans, soils, biomass burning, industrial sources, cattle and feedlots

Biosignatures on F, G, K and M planets

Parent star	Lifetime (yr)		
	CH_4	CH_3Cl	N_2O
Sun	4.4	0.6	2×10^2
F2V	3.9	0.5	1×10^2
K2V	15	2	3×10^2
M4.5V	1×10^3	2×10^3	7×10^2
M5V	6×10^3	6×10^2	7×10^5

CH_4 and CH_3Cl have much longer lifetimes on planets around M stars due to the particular slope of the incoming UV

N_2O depends directly on the incident stellar UV

Chemistry on a habitable planet around an active M star

Methane destruction in Earth's troposphere

$$O_3 + h\nu\ (\lambda < 310\ \text{nm}) \rightarrow O_2 + O^1D$$

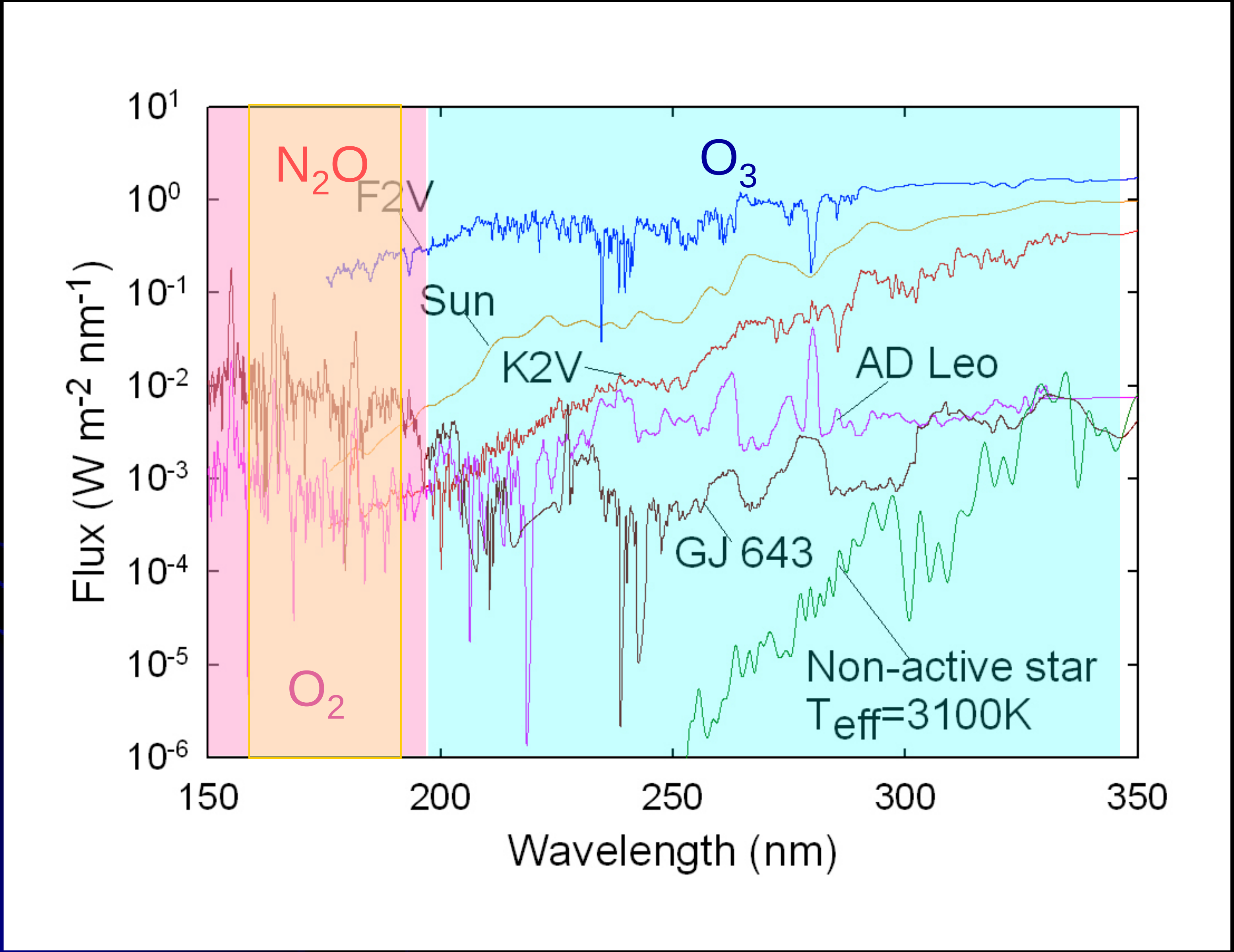
$$O^1D + H_2O \rightarrow 2\ OH$$

$$CH_4 + OH \rightarrow CH_3 + H_2O$$

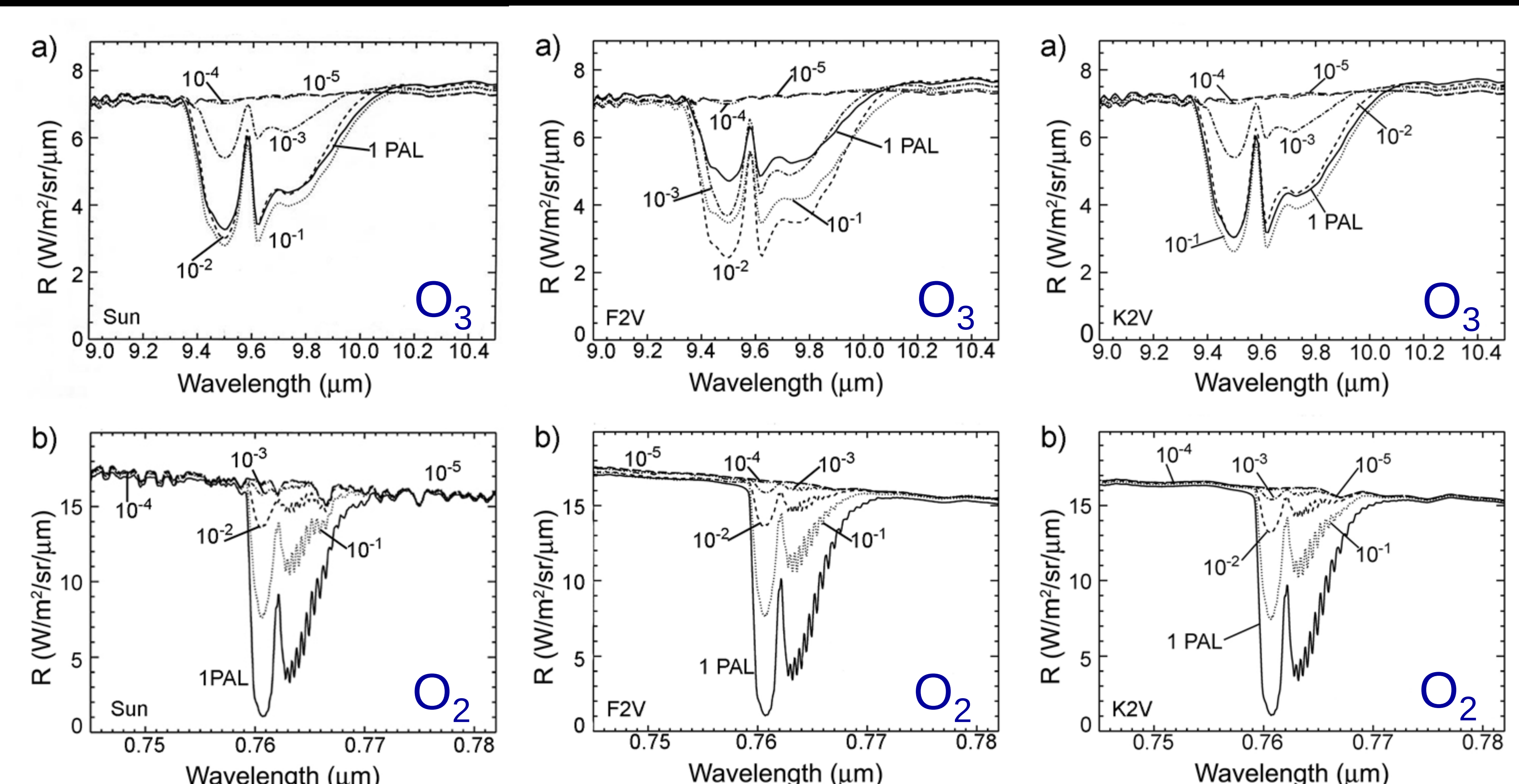
$$CH_3 + O_2 + M \rightarrow CH_3O_2 + M$$

$$\rightarrow \ldots \rightarrow CO\ (\text{or } CO_2) + H_2O$$

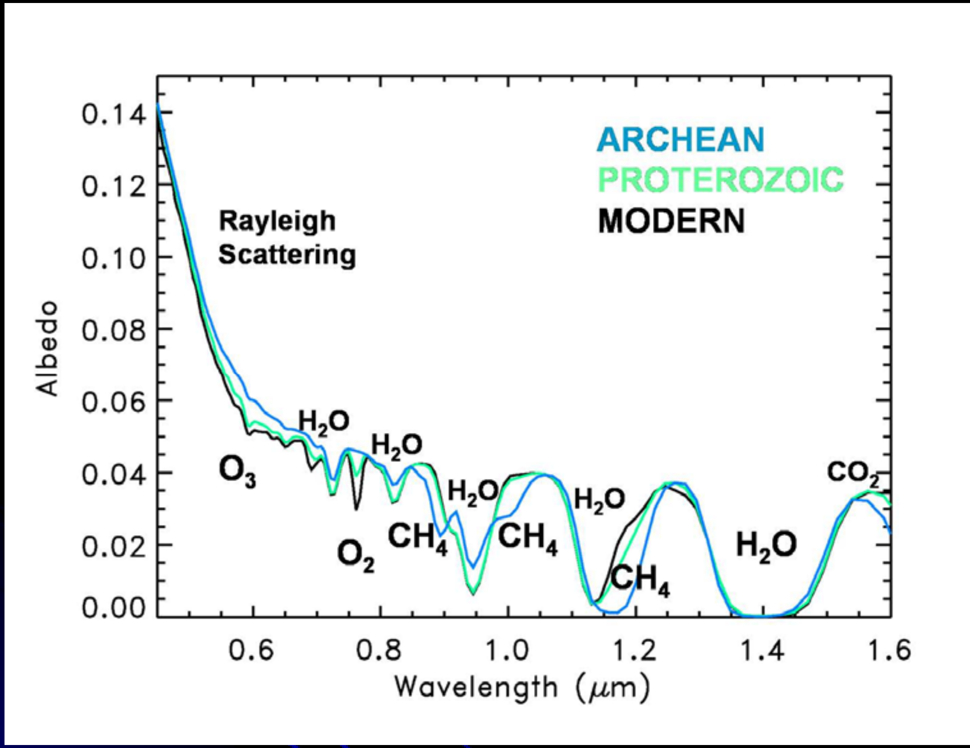
Photolysis of O_2 and O_3

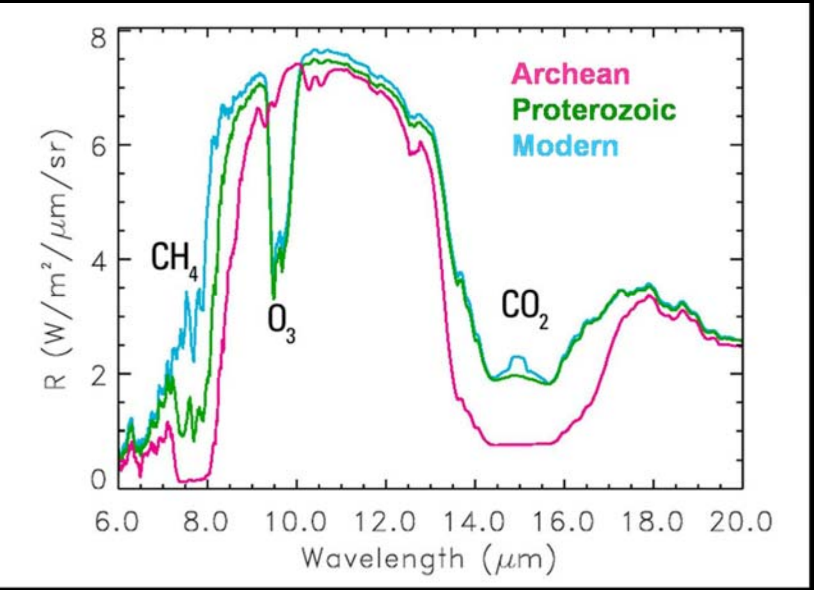


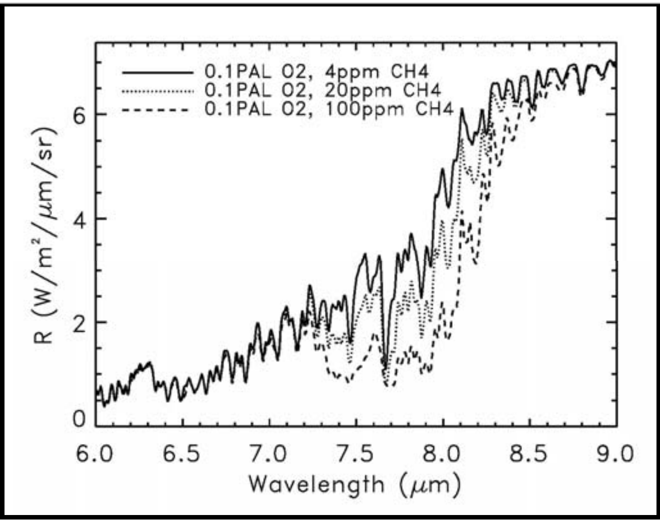
O_2 and O_3 signature in planets with different O_2 levels circling around F, G and K stars



The Earth in the past:
Mid Proterozoic (2.3-0.08 Ga)



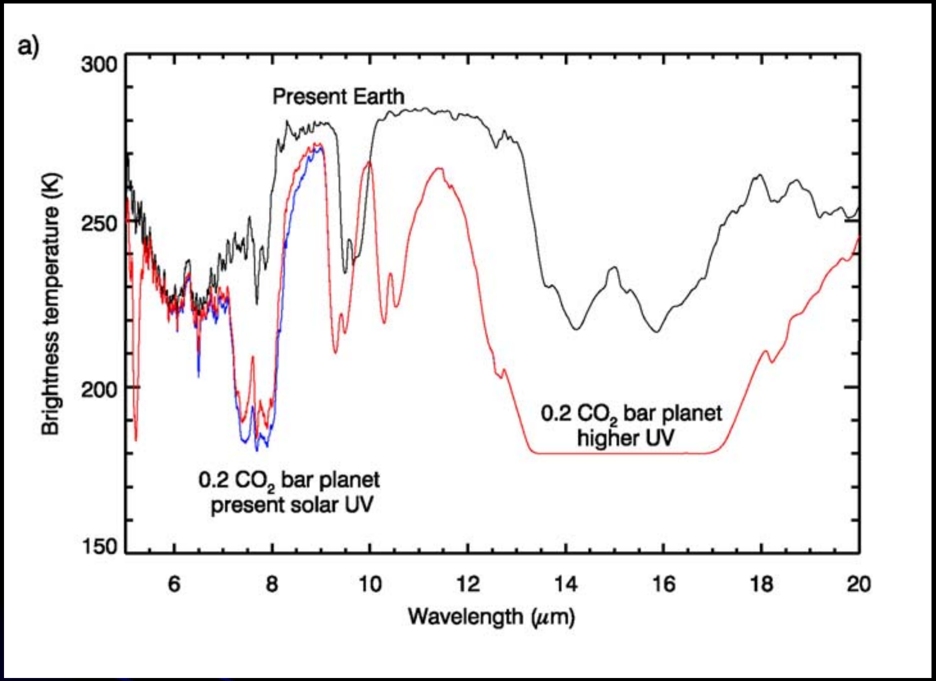


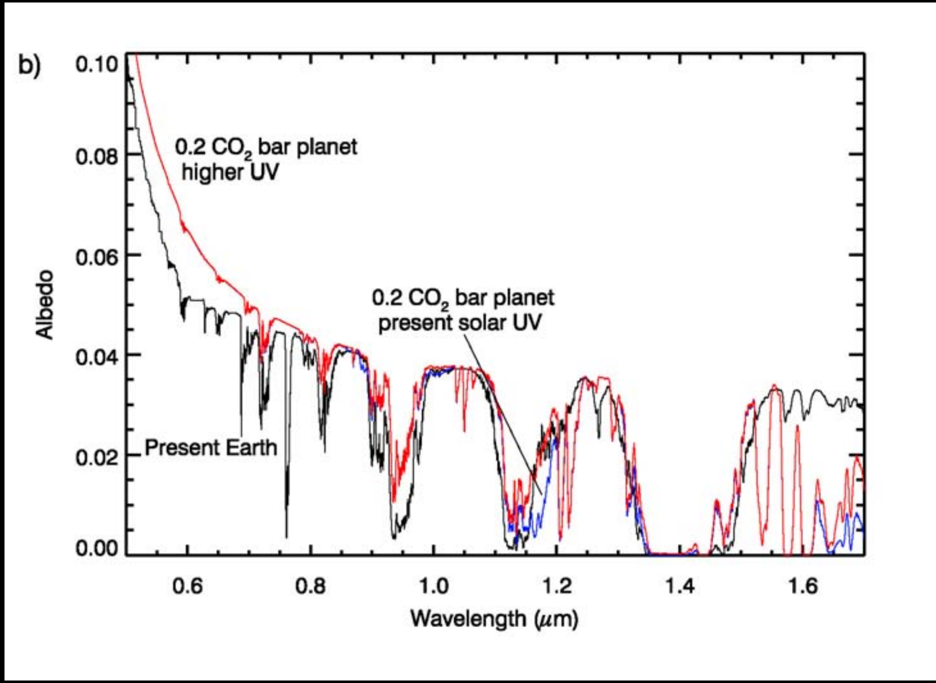


O.1 PAL of O_2, more CH_4

Pavlov et al. 2003 Geol. 31, 87

A CO_2 planet without life



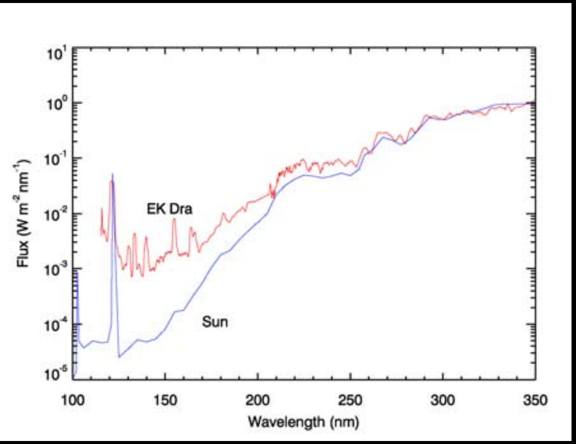


Atmosphere:

- $0.2\ CO_2$, $0.8\ N_2$
- 1bar surface pressure.
- CH_4 surface flux = 2.8×10^{13} gr/yr (5.35×10^{14} gr/yr)

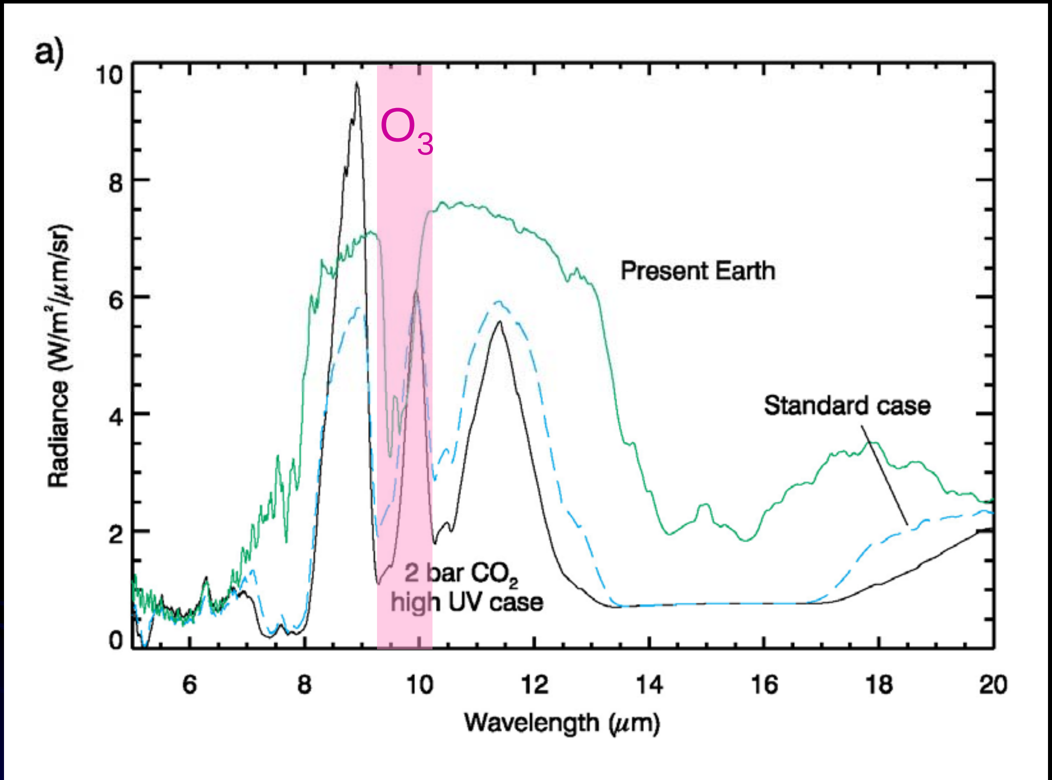
CH_4 with higher UV = 41 ppm

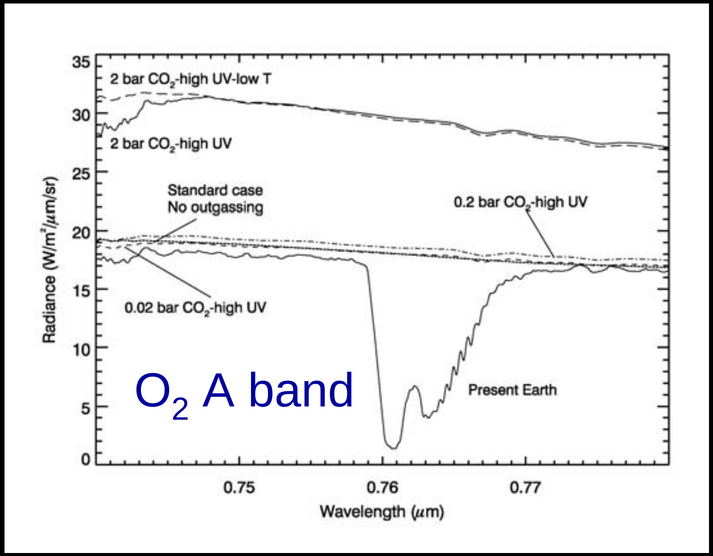
CH_4 with present solar UV = 140 ppm (1.6 ppm)



Segura et al. 2006 submitted A&A

A CO_2 planet without life





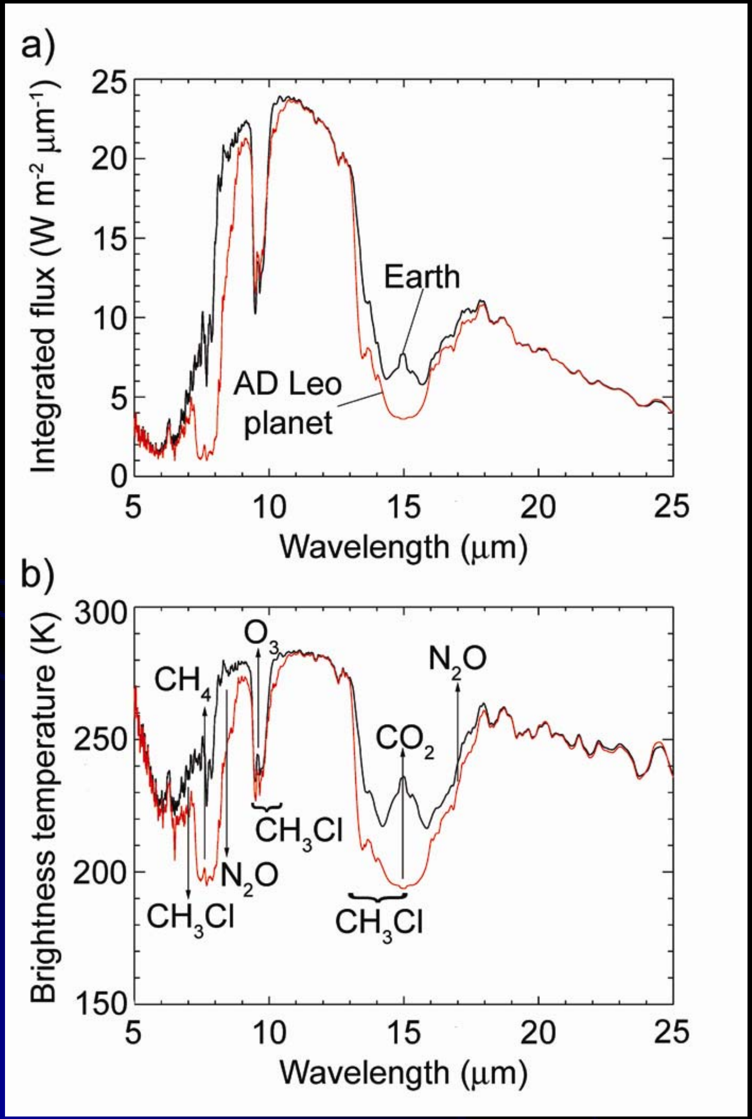
Atmosphere:

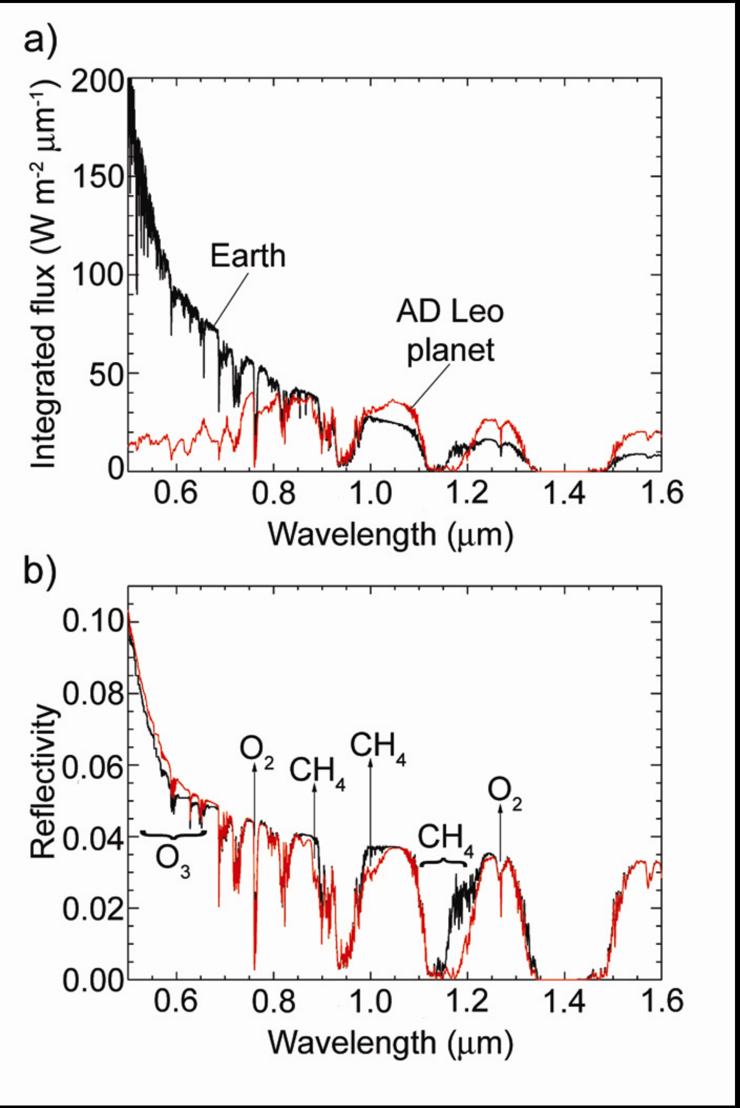
- 2 bars CO_2, 0.8 bars N_2
- 2.9 bars surface pressure.

Detailed H_2 budget should be considered to properly calculate the amount of O_2 and O_3 formed in a high CO_2 atmosphere

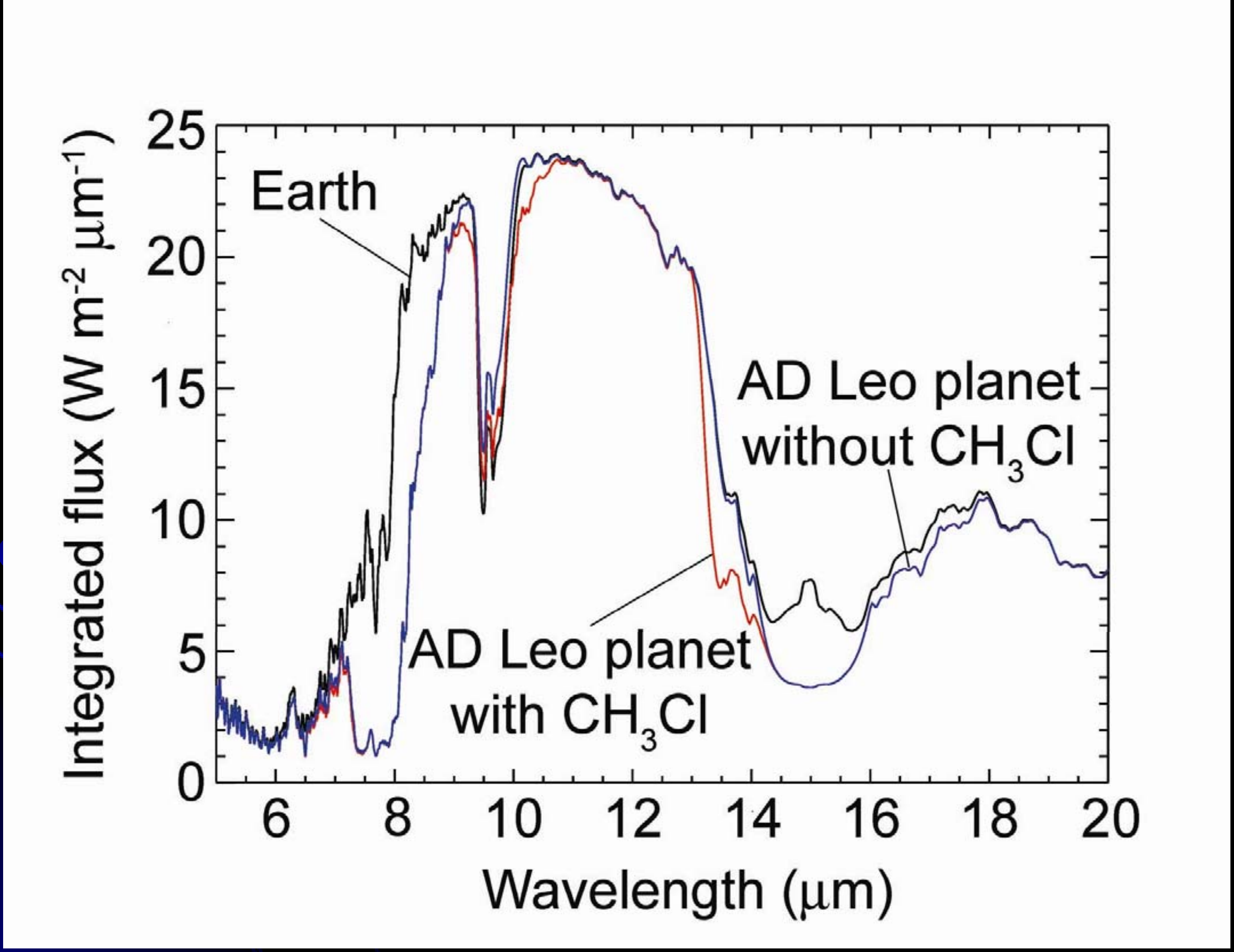
Segura et al. 2006 submitted A&A

A planet around AD Leo





Methyl chloride



Conclusions

- The planet's UV environment affects its atmospheric chemistry and the resultant spectrum in complicated and sometimes non-intuitive ways.
  - On high O_2 atmospheres methane lifetime depends on chemistry driven by the slope of the incoming UV.
  - On high CO_2 atmospheres CH_4 lifetime depends on the total incoming UV.
  - N_2O abundance depends directly on the incident UV from 100 to ~220 nm.
  - O_3 abundance increases with UV.
- Earth-like planets around the active M stars developed ozone layers similar to that on Earth and stars hotter than the Sun produce super ozone layers which effectively shield the surface.

Conclusions

- For active M star planets, CH_4 and CH_3Cl have significantly longer atmospheric lifetimes and may be more detectable than for Earth.
- For planets around quiescent M stars N_2O also has a significantly longer lifetime.
- The signature of O_3 from habitable planets around active M dwarfs may be detectable by missions like *TPF* or *Darwin*, along with the signatures of various reduced gases.
- The simultaneous detection of O_2 or O_3 and N_2O, CH_4, or CH_3Cl in the atmosphere of an M-star (or other extrasolar) planet would provide convincing evidence for the existence of extraterrestrial life.